

AN INVESTIGATION OF THE VIRTUAL MASS  
OF A CYLINDER VIBRATING IN WATER

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DAVID A. ROGERS  
AND  
MACLEAN C. SHAKSHOBER  
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An Investigation of the Virtual Mass

of a

Cylinder Vibrating in Water

by

DAVID A. ROGERS

"

LIEUTENANT, U. S. NAVY

B. S. UNITED STATES NAVAL ACADEMY (1945)

and

MACLEAN C. SHAKSHOBER

LIEUTENANT, U. S. Navy

Submitted to the Department of Naval Architecture and Marine Engineering on  
May 25, 1953 in partial fulfillment of the requirements for the degree of  
Naval Engineer.

---

Professor F. M. Lewis,---Thesis Supervisor

---

Chairman of Department Committee on Graduate Students





ABSTRACT

AN INVESTIGATION OF THE VIRTUAL MASS OF A CYLINDER  
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by

DAVID A. ROGERS

MACLEAN C. SHAKSHOBER

LIEUTENANT, U.S. NAVY

and

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Submitted to the Department of Naval Architecture and Marine Engineering on May 25, 1953 in partial fulfillment of the requirements for the degree of Naval Engineer.

The object of this thesis is to experimentally investigate the virtual mass of a hollow cylinder vibrating in water.

A lucite cylinder was magnetically vibrated in air and water at various length to diameter ratios and the frequency of vibration for as many modes as possible, up to five, recorded. No attempt was made to measure amplitude. The ratio of added water mass to displaced water mass was computed from the frequencies and compared with analytical results.

The investigation shows that end effects have a very great influence on virtual mass. As the length to diameter ratio is decreased, the added virtual water mass is decreased. There is also a decrease in virtual water mass as frequency is increased at constant length to diameter ratios.

A ratio of the measured virtual water mass to analytical, called K, was computed and found to be a function of  $L/D$  and mode number.

It is recommended that further investigations using bodies of revolution whose ends have zero area such as ellipsoids be made. It would be desirable to use equipment to permit measuring amplitude as well as frequency.

Where data is available, it is recommended that an attempt to calculate the frequencies of an actual hull such as a submarine be made, correcting the analytical virtual water mass by the applicable K values.

Thesis Supervisor: Professor F. M. Lewis  
Title: Professor of Marine Engineering

AN INVESTIGATION OF THE EFFECTS OF A CHANGING  
VIBRATING IN WATER

by

WILLIAM V. BRIDGES

DAVID L. BRIDGES

LESTER W. BRIDGES

LESTER W. BRIDGES

Submitted to the Department of Physics (Acoustics and Vibration) on  
May 22, 1952 in partial fulfillment of the requirements for the degree of  
Master of Science.

The object of this thesis is to experimentally investigate the effects  
of a harmonic vibration vibrating in water.

A simple vibrator was experimentally vibrated in air and water at various  
frequencies to determine the effects of the frequency of vibration on the sound  
pressure level, up to 1000 cycles per second. It was found that the sound  
pressure level in water was higher than in air at the same frequency.

The investigation shows that the effects of a very small vibration  
in water are. As the frequency of vibration is increased, the sound  
pressure level in water is decreased. There is also a decrease in the sound  
pressure level in water as the frequency is increased.

A table of the sound pressure level in water is given in table 1. It was  
found that the sound pressure level in water is higher than in air at the same frequency.

It is recommended that further investigation be made on the effects of  
vibration in water. It would be desirable to make a study of the effects of  
vibration in water on the human ear.

These data are useful, it is recommended that an attempt be made to  
determine the effects of a small vibration in water on the human ear. The  
effects of a small vibration in water on the human ear are of great interest.

These data are useful, it is recommended that an attempt be made to  
determine the effects of a small vibration in water on the human ear.

Cambridge, Massachusetts  
May 25, 1953

Professor Earl B. Millard  
Secretary of the Faculty  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer,  
we herewith submit a thesis entitled "An Investigation of the Virtual Mass  
of a Cylinder Vibrating in Water."

Respectfully,

---

David A. Rogers  
Lieutenant, U. S. Navy

---

MacLean C. Shakshober  
Lieutenant, U. S. Navy

University of California  
Berkeley, California  
May 22, 1952

Professor Paul H. Hildebrand  
University of the Pacific  
Stockton, California

Dear Sir:

In accordance with the requirements for the degree of Master of Science,  
we request that you submit a thesis entitled "An Investigation of the Physical Properties  
of a Synthetic Fibrous Material."

Respectfully,  
\_\_\_\_\_  
Lester R. Hildebrand

\_\_\_\_\_  
Lester R. Hildebrand  
May 22, 1952

\_\_\_\_\_  
Lester R. Hildebrand  
May 22, 1952



## TABLE OF CONTENTS

SECTION	CONTENTS	PAGE
	TABLE OF FIGURES .....	1
I.	INTRODUCTION .....	2
II.	PROCEDURE .....	4
III.	RESULTS .....	8
IV.	DISCUSSION OF RESULTS .....	13
V.	RECOMMENDATIONS .....	15
VI.	APPENDIX .....	16
	A. Details of Procedure .....	17
	B. Summary of Data and Calculations .....	21
	C. Sample Calculations .....	29
	D. Original Data .....	33
	E. Bibliography .....	42

# TABLE OF CONTENTS

PAGE	CHAPTER	PAGE
I	GENERAL PRINCIPLES OF THE THEORY OF THE EARTH	
II	THE EARTH'S CRUST AND ITS DEFORMATION	11
III	THE EARTH'S MANTLE AND ITS DEFORMATION	11
IV	THE EARTH'S CORE AND ITS DEFORMATION	11
V	THE EARTH'S SURFACE AND ITS DEFORMATION	11
VI	THE EARTH'S INTERIOR AND ITS DEFORMATION	11
VII	THE EARTH'S EXTERIOR AND ITS DEFORMATION	11
VIII	THE EARTH'S HISTORY AND ITS DEFORMATION	11
IX	THE EARTH'S FUTURE AND ITS DEFORMATION	11
X	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XI	THE EARTH'S PAST AND ITS DEFORMATION	11
XII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XIII	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XIV	THE EARTH'S PAST AND ITS DEFORMATION	11
XV	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XVI	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XVII	THE EARTH'S PAST AND ITS DEFORMATION	11
XVIII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XIX	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XX	THE EARTH'S PAST AND ITS DEFORMATION	11
XXI	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXII	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXIII	THE EARTH'S PAST AND ITS DEFORMATION	11
XXIV	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXV	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXVI	THE EARTH'S PAST AND ITS DEFORMATION	11
XXVII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXVIII	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXIX	THE EARTH'S PAST AND ITS DEFORMATION	11
XXX	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXXI	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXXII	THE EARTH'S PAST AND ITS DEFORMATION	11
XXXIII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXXIV	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXXV	THE EARTH'S PAST AND ITS DEFORMATION	11
XXXVI	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XXXVII	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XXXVIII	THE EARTH'S PAST AND ITS DEFORMATION	11
XXXIX	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XL	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XLI	THE EARTH'S PAST AND ITS DEFORMATION	11
XLII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XLIII	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XLIV	THE EARTH'S PAST AND ITS DEFORMATION	11
XLV	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XLVI	THE EARTH'S PRESENT AND ITS DEFORMATION	11
XLVII	THE EARTH'S PAST AND ITS DEFORMATION	11
XLVIII	THE EARTH'S FUTURE AND ITS DEFORMATION	11
XLIX	THE EARTH'S PRESENT AND ITS DEFORMATION	11
L	THE EARTH'S PAST AND ITS DEFORMATION	11

TABLE OF FIGURES

	PAGE
Figure I. Schematic .....	5
Figure II. Ratio of Virtual Water Mass to Displaced Mass vs. $\eta$ ...	9
Figure III. Mass Ratio vs. $L/D$ for Constant $\eta$ .....	10
Figure IV. $K$ vs $\eta$ for Constant $L/D$ .....	11
Figure V. $K$ vs $L/D$ for Constant $\eta$ .....	12
Figure VI. Photographs of 2-noded Frequency .....	40
Figure VII. Photograph of 6-noded Frequency .....	41

# TABLE OF CONTENTS

Figure I.	.....	1
Figure II.	.....	2
Figure III.	.....	3
Figure IV.	.....	4
Figure V.	.....	5
Figure VI.	.....	6
Figure VII.	.....	7



## I. INTRODUCTION

When immersed in a dense fluid, such as water, a body vibrates as though it had undergone an increase in mass. This increase in mass is due to the flow of fluid about the body as it moves.

Several analytical methods of computing the virtual mass of a body vibrating in a dense fluid have been presented.<sup>(1, 2)</sup> These methods are based on the assumption of potential flow about the body. Unless the body is of uniform shape with pointed ends, i.e. an ellipsoid, it is not presently possible to compute analytically the virtual mass because of the flow about the ends being highly rotational.

A submerged submarine must vibrate as a free-free body at a frequency determined by its virtual mass as described above. When vibrating horizontally, its virtual mass will be somewhat lower than that computed on the basis of no end losses because of flow about the ends.

Professor Frank M. Lewis has presented a method for determining the virtual mass based on an ellipsoid which may be corrected for other shapes.<sup>(1)</sup> Dr. H. M. Schauer of the Underwater Explosion Research Division, Norfolk Naval Shipyard, has done likewise for a cylinder with no end flow. Mr. E. B. Moullin and Mr. A. D. Browne, in a paper presented before the Cambridge Philosophical Society in 1928<sup>(3)</sup> gave the results of their investigation of the periods of a free-free bar of rectangular cross section vibrating in water. In their experiments they used long bars which had length to depth ratios of from 26 to 39. Using such long bars they found that flow about the ends did not have any appreciable effect on the virtual mass as analytically computed. However, they did not investigate lower length to depth ratios. They found that the virtual mass is not affected by depth when below about two diameters.

1946年10月1日

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The following is a report on the experimental determination of the virtual mass of a circular cylinder for several length to diameter ratios while vibrating in water.

The following is a report on the experimental investigation of the  
virtual work of a rotating cylinder for several lengths of the cylinder twice  
the length of the cylinder.

2. 5. 1944



## II. PROCEDURE

In this section the steps followed to obtain the desired results are described. The procedure consists of two parts, experimental and analytical. Details of the procedure are presented in the Appendix.

### Experimental Procedure

From "The Theory of Sound" by Rayleigh<sup>(4)</sup> the appropriate equations were used to obtain the nodal and anti-nodal points of a free-free bar. Using the frequency equation for a free-free bar

$$f = \frac{n^2}{2\pi} \left[ \frac{EK^2}{\delta} \right]^{1/2} \quad (1)$$

the first five modes were computed to give an approximation of the natural frequencies.

To vibrate the cylinder mechanically would require a motor with a speed range of 1800 to 60,000 revolutions per minute. For this reason, magnetic vibration of the bar was by far the preferred method. Schematics of the apparatus are shown in Figure I.

A Lucite plastic tube 52.7 inches long with an outer diameter of 2 inches and an inner diameter of 1.75 inches was used for the first test. On the end of the cylinder was wrapped some small diameter soft iron wire to permit magnetic excitation. The amount of wire was not great enough to affect the frequency or mass of the bar. By experimenting with various types of pickups, it was found that a seismic crystal gave the best results. The pickup was very light in weight and very sensitive to vibration. This particular pickup was a Brush seismic crystal used on the sounding board of an electric guitar. The pickup was mounted on the inside of the cylinder at the opposite end of

Experimental Results

In this section the results of the experiments are described. The general character of the results is summarized in Table I. Details of the experiments are given in the Appendix.

General Remarks

From the results of the experiments it is evident that the results are very similar to those obtained in the case of a single crystal. The results are summarized in Table I. Details of the experiments are given in the Appendix.

$$M = \frac{1}{2} \left[ \frac{1}{2} \left( \frac{1}{2} \right) \right]$$

(1)

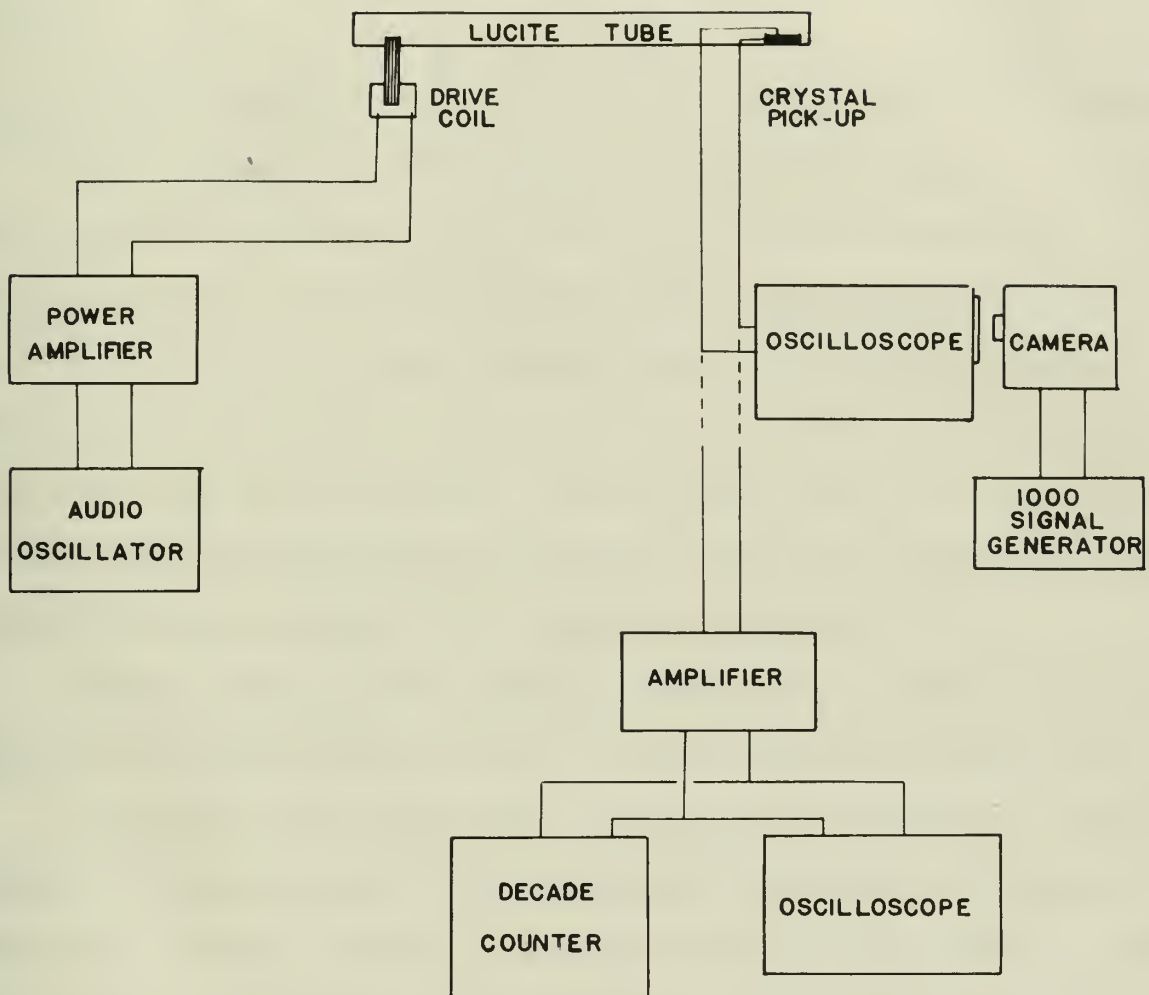
The first three results are given in Table I. The results are summarized in Table I. Details of the experiments are given in the Appendix.

To obtain the results summarized in Table I, the results are summarized in Table I. Details of the experiments are given in the Appendix.

The results are summarized in Table I. Details of the experiments are given in the Appendix.

FIG. I  
SCHEMATIC

MAY 8, 1953, MCS







the exciting wire. A small hole was drilled at a nodal point through which the wires from the pickup were run.

An audio oscillator with a frequency range of 20 to 20,000 cycles per second was used to drive an electro-magnet. The output of the audio oscillator was amplified in a power amplifier and this was used to drive the electro-magnet. The output of the crystal pickup was put into a cathode ray oscilloscope where the signal was peaked for resonance. Unfortunately, due to radiation, frequencies above 1600 cycles per second could not be detected.

Two different types of frequency measurement were employed to compute the frequency of vibration, both of which gave very accurate and like results. The first method was to take the output of the pickup and put it on the vertical plates of the CRO. When a resonant signal was obtained, a picture of the frequency was taken with no horizontal sweep. The camera used was a very high speed model with no shutter. The camera had a built-in timing light of 1000 cycles per second which showed on the film. The frequency was then computed from the developed film by counting the cycles.

The other method of determining the frequency was to take the amplified output of the crystal pickup and put it into an electronic decade counter.

To compute the air frequencies, the cylinder was suspended by strings located at the nodal points. The electro-magnet was placed as close as possible to the soft iron windings. To prevent banging of the cylinder, a rubber band was used as a standoff. The frequencies were recorded as described above.

For the water tests, the cylinder was immersed seven diameters in the towing tank in the M. I. T. Hydrodynamics Laboratory. This depth ensured that no surface effects would be present. The cylinder was anchored by two strings at the nodes.

the working fluid. A small hole was drilled at a radial point between which the stress from the bridge was zero.

An audio oscillator of 1000 cycles per second was used to drive an electro-magnet. The output of the audio oscillator was amplified in a power amplifier and this was used to drive the electro-magnet. The output of the crystal pickup was fed into a vacuum tube oscillator where the signal was needed for transmission. Inductively coupled to this oscillator, a second 1000 cycle per second coil was fed back to the oscillator. The different types of frequency measurement were employed to compare the frequency of vibration with that given very accurate and low frequency. The first method was to take the output of the pickup and put it in the center of the glass of the SGO. When a resonant signal was obtained, a picture of the frequency was taken with an oscilloscope. The second method was a very high speed wheel with an indicator. The wheel was a half-inch in diameter of 1000 cycles per second which showed on the film. The frequency was then compared from the developed film by counting the cycles.

The other method of determining the frequency was to take the amplified output of the crystal pickup and put it into an electronic device which compared the frequency of the oscillator with the frequency of the pickup. The device was located at the radial bridge. The electro-magnet was placed at about the center of the hole from which the pickup was taken. To prevent loading of the oscillator, a rubber band was used as a support. The frequencies were recorded on a oscilloscope.

For the water tests, the cylinder was mounted with the piston in the testing tank in the M. I. T. Hydrodynamic Laboratory. This setup was used for no further effects could be possible. The cylinder was supported by two struts at the bottom.

The same procedure was followed using cylinders of 40, 38, 30, 28, and 22 inches, and for a 42-inch bar with six-inch conical ends.

#### Analytical Procedure

The ratio of the added water mass to displaced water mass,  $M_v/M_o$ , was computed directly from the observed frequencies as explained in Details of Procedure.

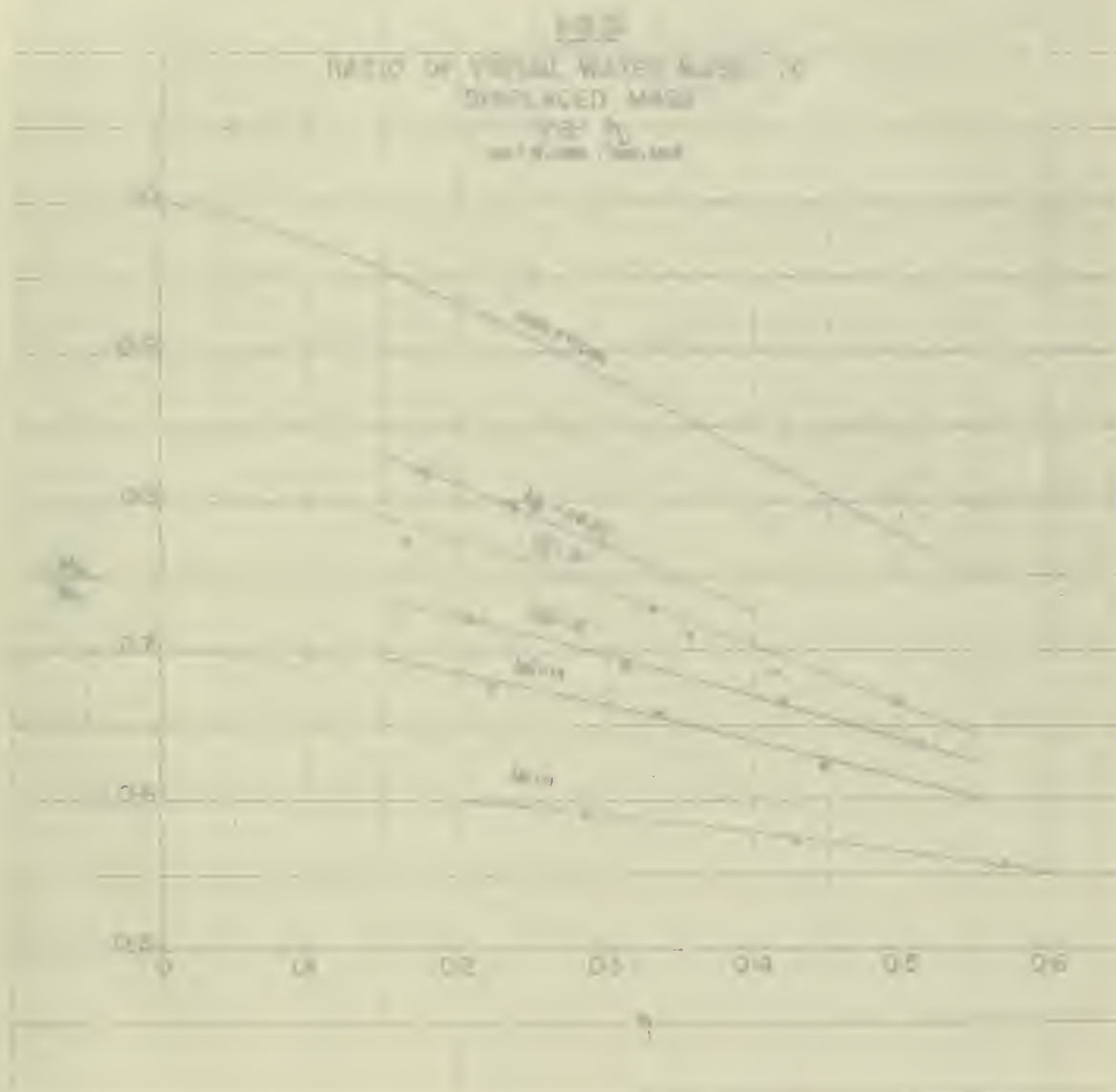
A correction factor K was then calculated, where K is the ratio of measured  $M_v/M_o$  to that computed by Dr. H. M. Schauer. (2)





### III. RESULTS

The results are plotted as shown in Figs. II through V.



• It doesn't hurt at all to get a tattoo and it's not

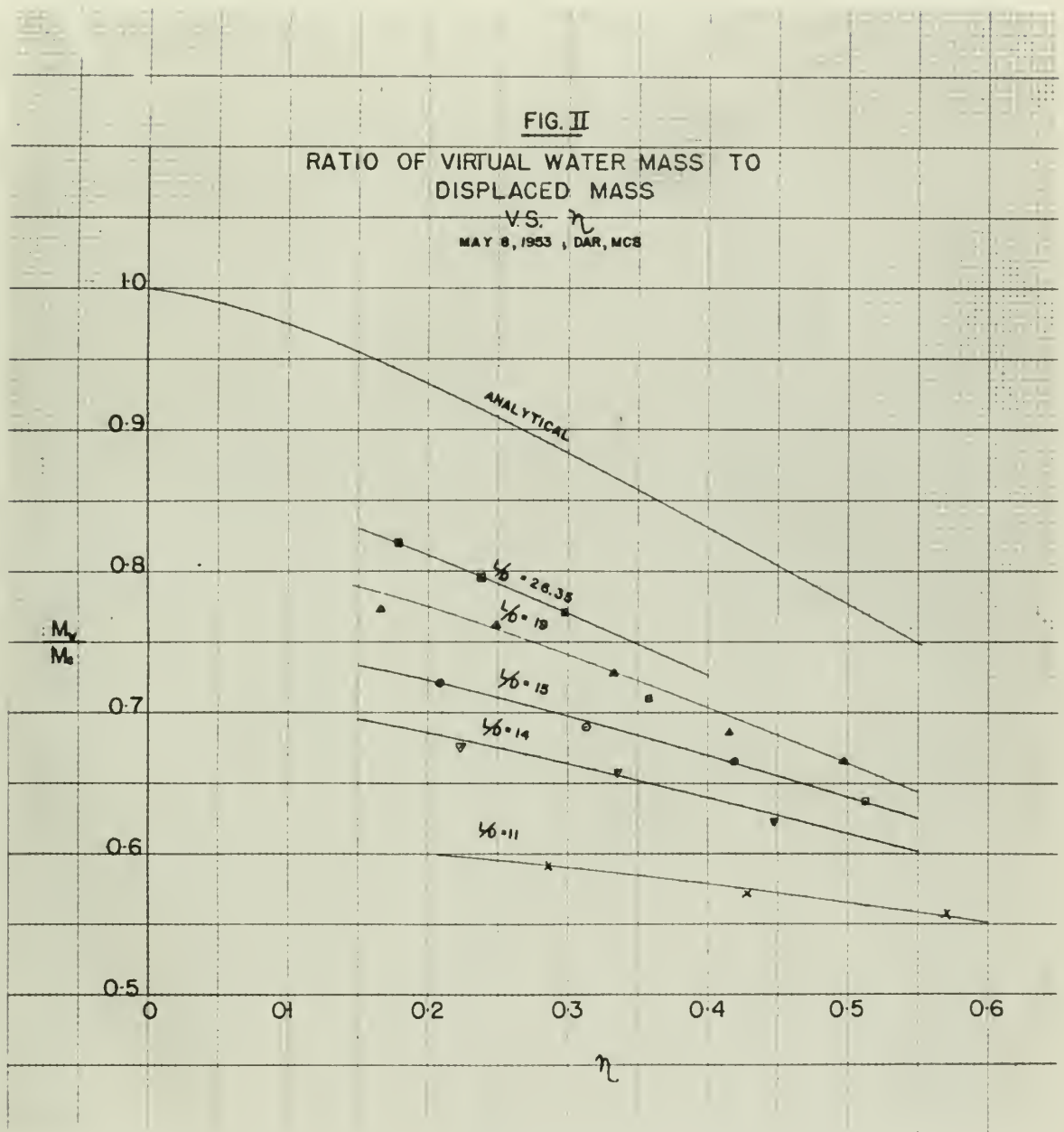






FIG. III  
MASS RATIO V.S.  $L/D$  FOR  
CONSTANT  $\eta$   
MAY 8, 1953, DAR, MCS

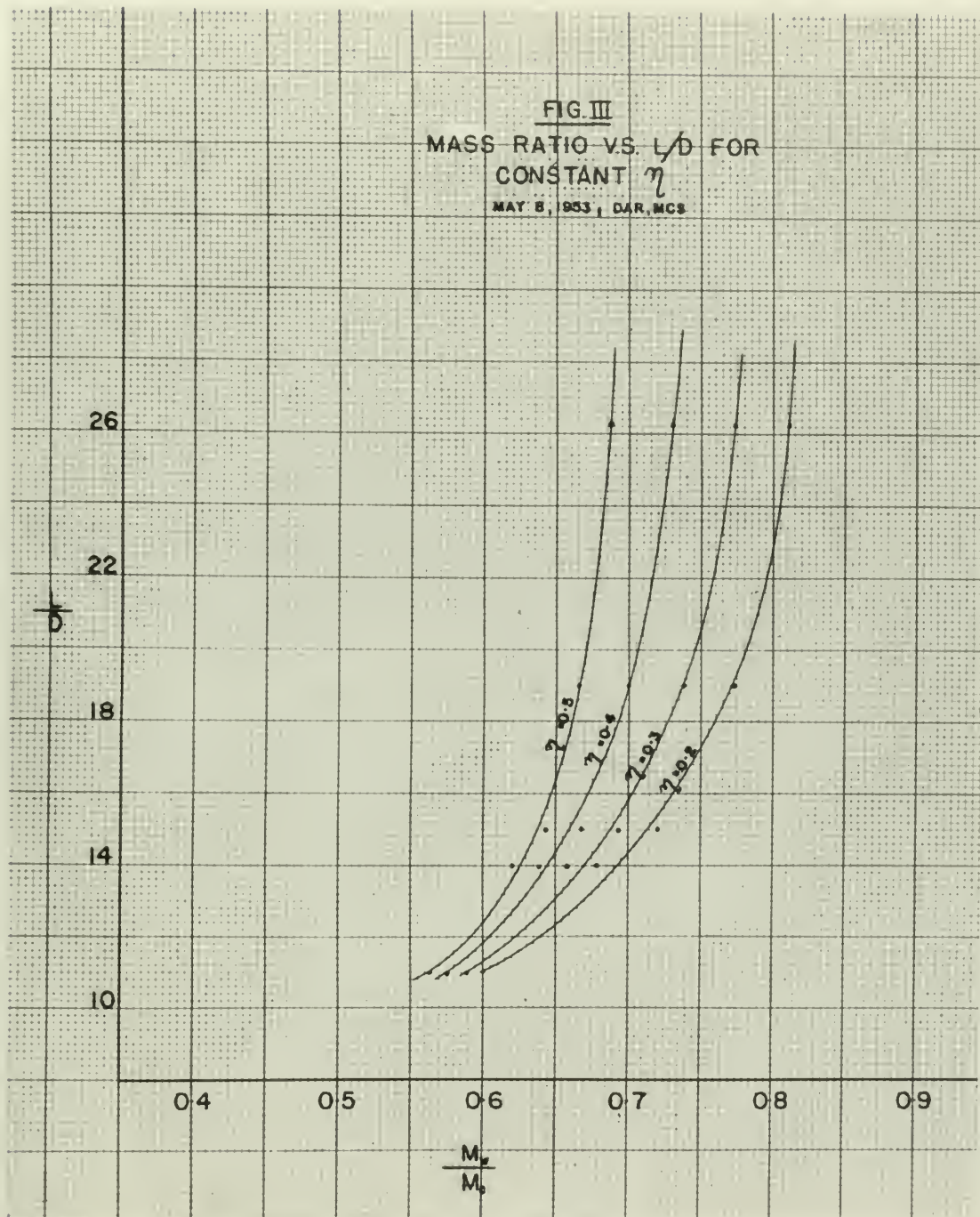




FIG. IV

K V.S.  $\eta$  FOR CONSTANT  $\frac{L}{D}$   
MAY 8, 1953, DAR, MGS

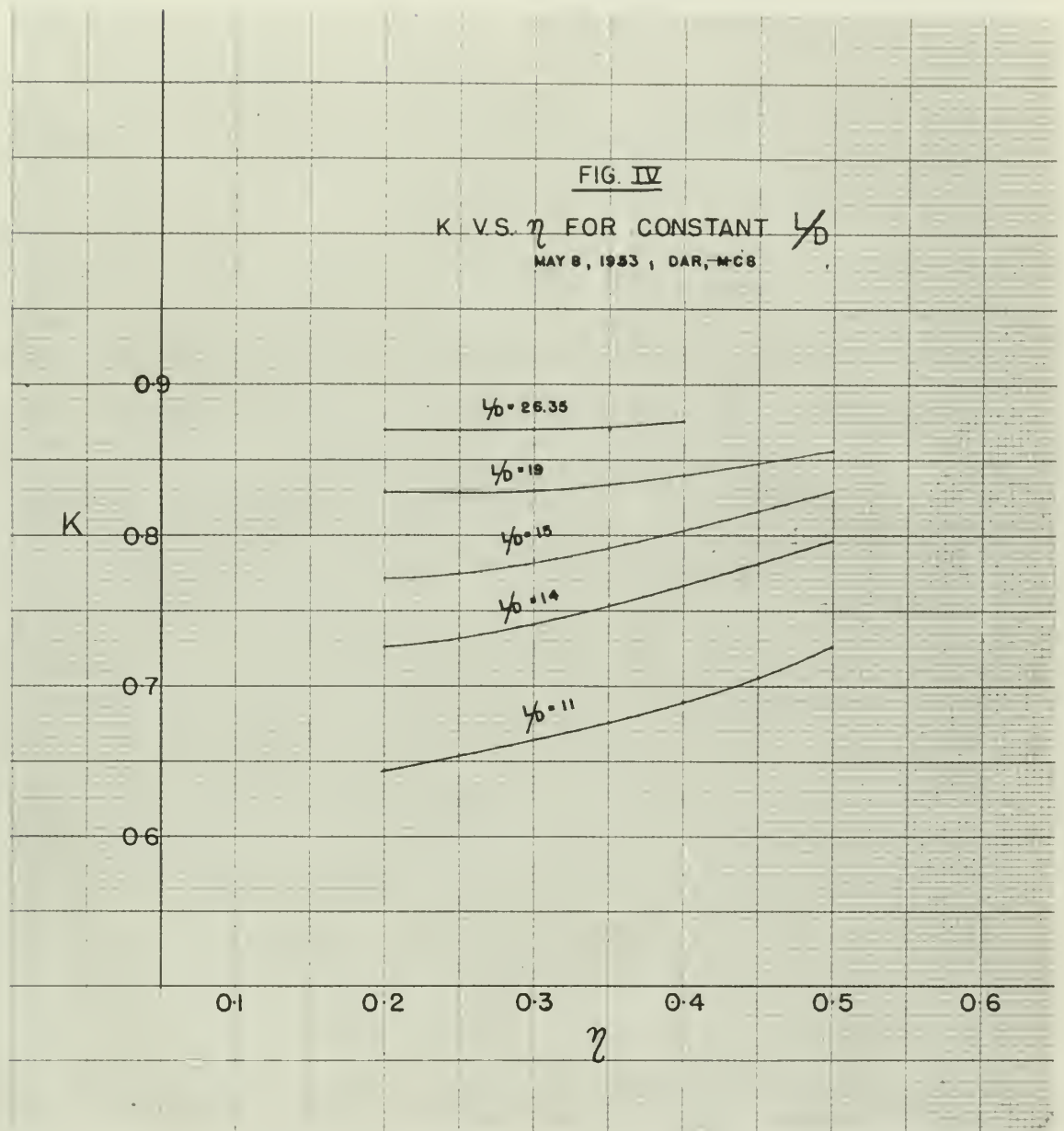
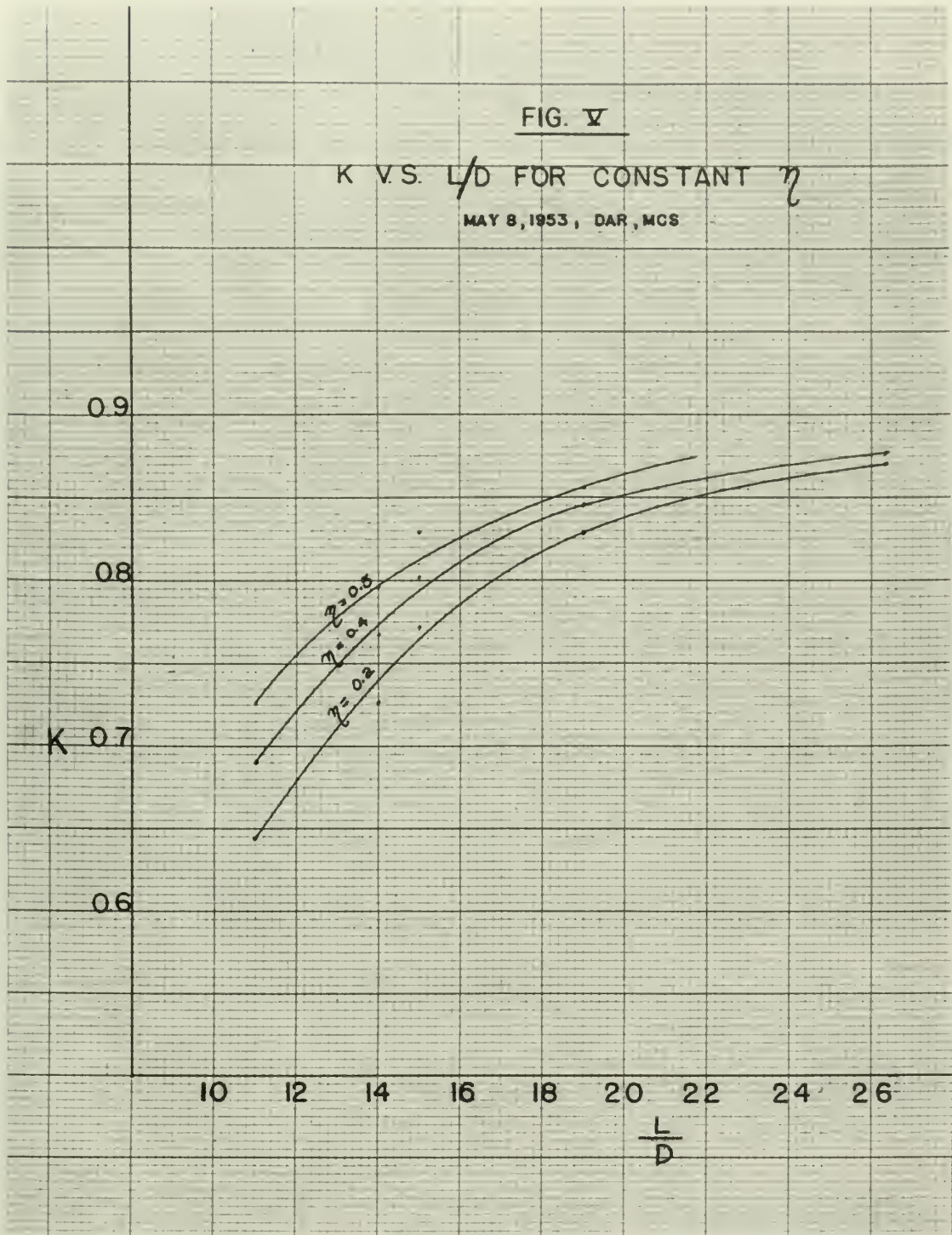




FIG. V

K V.S.  $L/D$  FOR CONSTANT  $\eta$

MAY 8, 1953, DAR, MCS







#### IV. DISCUSSION OF RESULTS

The results shown plotted in figures II through V indicate that the ends have a large influence on the value of the ratio of added water mass to the displaced water mass, i.e.  $M_w/M_c$ . As the length to diameter ratio is decreased, the value of K, (the ratio of measured  $M_w/M_c$  to the  $M_w/M_c$  calculated by Dr. Schauer), decreases rapidly for a given value of  $\eta$ . However, K increases for increasing  $\eta$  at constant L/D.

K is based on an analytical curve which assumes a potential flow, and therefore irrotational, with no flow about the ends. Thus K may be considered a measure of the end flow and of rotationality. For a cylinder with flat ends a large portion of K can probably be attributed to flow of the fluid about the ends.

Just how much of the difference from analytical values can be attributed to end flow is difficult to say from these experiments. An inspection of the test results of the cylinder with conical ends indicates that end flow is not the only contributing factor since the area at the ends of the cones is substantially zero. However, due to the abrupt change in shape of the body where the cones are joined to the cylinder, a certain amount of spilling of fluid toward the ends will occur.

Due to the large effects of L/D on the value of  $M_w/M_c$  it appears that a direct application of Dr. Schauer's equation is not feasible unless the body is very long relative to its breadth.

Professor F. M. Lewis<sup>(1)</sup> has shown that the added water mass per foot of length for an ellipsoid is

IV. DISCUSSION OF RESULTS

The results shown in Table II show that the  
 only large difference in the value of  $\sqrt{V}$  is  
 to the highest value, i.e.  $\sqrt{V} = 0.5$ . As the length of the  
 distance, the value of  $\sqrt{V}$  (the value of  $\sqrt{V}$  is the  $\sqrt{V}$  value  
 calculated for the distance) decreases rapidly for a given value of  $\sqrt{V}$ .  
 It is based on an empirical curve which shows a constant  $\sqrt{V}$  and  
 therefore constant, with no change in the value. Thus it can be seen  
 that a measure of the rate of change of  $\sqrt{V}$  for a given value  
 that with a large portion of it was probably in the value of the  
 field about the body.  
 Just how much of the difference from empirical values can be attrib-  
 uted to the fact is difficult to say from these experiments. An inspection  
 of the last results of the constant with constant rate indicates that and  
 that is not the only contributing factor since the rate of the rate of the  
 curve is substantially zero. However, due to the change in the rate of  
 the body where the curve was taken in the experiment, a certain amount of  
 splitting of field around the body will occur.  
 Due to the large values of  $\sqrt{V}$  at the value of  $\sqrt{V} = 0.5$  it appears that  
 a direct application of the Gaussian's equation is not feasible unless the  
 body is very large relative to the distance.  
 Professor F. R. Jones<sup>(1)</sup> has shown that the value of  $\sqrt{V}$  for  
 test of length for an electron is



$$M_w = CJ\pi B^2 \gamma_w \quad (2)$$

where

C = Section inertia coefficient

B = Half beam or radius of ellipsoid at section

$\gamma_w$  = Specific weight of fluid

J =  $\frac{\text{Actual K. E. surrounding fluid}}{\text{K. E. of fluid if flow is two dimensional}}$

Now for a cylinder C = 1 and we can write

$$M_w = J\pi R^2 \gamma_w L \quad (3)$$

and

$$\frac{M_w}{M_c} = \frac{J\pi R^2 \gamma_w L}{\pi R^2 \gamma_w L} \quad (4)$$

so that

$$J = \frac{M_w}{M_c} \quad (5)$$

It was found that if Prof. Lewis' J factor is multiplied by our K, a fairly decent approximation to the actual frequency of a submerged body can be computed. A computation was made of the submerged frequency of a 42-inch body having 6-inch cones at each end of a cylindrical middle body 30 inches long.

Using Prof. Lewis' J factor multiplied by K for an L/D ratio of 21 at  $\eta = .15$ , the computed two noded frequency was 68.9 c.p.s. and the experimentally measured value was 70 c.p.s. For the three noded frequency the computed value was 187 c.p.s. and the measured value was 188 c.p.s.

Although this method gives very good results in the case tested, further investigation is required to determine its limits of application. Similar results would have been found using Dr. Schauer's  $M_w/M_c$  in a like manner.

(2)

18

479:1166 479:1167 479:1168

...to the ... of ...

What is the degree of freedom?  $\chi^2$

11/11/1911 - 11/11/1911

Page 100 of 100

CULT

1871

2009

4)

THE  
JOURNAL  
OF  
THE  
ROYAL ANTHROPOLOGICAL INSTITUTE

(2)

10

303

It was found that if the test is repeated, the results are similar to the first test.

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100

THE 12th of May 1964 was a day of celebration for the people of the world.

12. The novel is the last of the "The Last of the Mohicans" series.

ALL material before the Commission shall be in the English language.

\* \* \* \* \* The difference between the 1990 and 1991 values was 10.7%.

It is a common mistake to think that the only way to avoid the problems of the first two methods is to use a third method, the method of least squares. This method is also based on the assumption that the data are normally distributed, and it is not immune to the problems of the first two methods. In fact, the method of least squares is often used in conjunction with the method of moments, and the two methods are often used together to estimate the parameters of a distribution.

[illegible]

...and the ...

## V. RECOMMENDATIONS

In view of the large discrepancy between values of theoretical mass found by analytical means and those measured, it is recommended that an investigation similar to this be made of families of bodies of revolutions having ends whose section decreases to zero.

The measurement of the virtual mass of bodies which do not have complete radial symmetry is much more difficult since pains must be taken to insure that the vibrations are limited to the plane desired. However, it is recommended that where data exists on the vibration of submerged bodies such as submarines, an attempt be made to apply the correction,  $K$ , to compute their frequencies.

1. INTRODUCTION

In view of the large number of persons who are  
interested in the study of the history of the  
United States, it is necessary to have a  
knowledge of the history of the United States.  
The purpose of this book is to give a  
brief history of the United States from  
the time of the first settlement to the  
present. It is written for the use of  
students in the history of the United States.  
It is written in a simple and plain  
language, so that it can be understood  
by all. It is written in a simple and  
plain language, so that it can be  
understood by all. It is written in a  
simple and plain language, so that it  
can be understood by all.

VI. APPENDIX



## CHAPTER IV

The first part of the chapter is devoted to a general

discussion of the various methods of determining the

value of the various factors.

The second part of the chapter is devoted to a

discussion of the various methods of determining the

value of the various factors.

The third part of the chapter is devoted to a

discussion of the various methods of determining the

value of the various factors.

## CHAPTER V

## A. DETAILS OF PROCEDURE

### Selection of Tubing

Since the object of this investigation is to determine the virtual added mass of water, it is desirable that the cylinder be made of a material having a low specific gravity. Thus the added water mass will be a large fraction of the total virtual mass of the body. In order that the frequencies of the cylinder will not be excessively high, the material should have a relatively low modulus of elasticity.

As a result of these considerations, it was decided that the cylinder should be constructed of Lucite. The specific gravity of Lucite is 1.18 and has a modulus of elasticity in the order of  $5 \times 10^5$  pounds per square inch.

### Effect of Added Masses

The weight of the soft iron wire was .373 ounces and covered three-fourths of an inch of the cylinder. The weight of the crystal pick-up and clamp used to hold it securely in place was .303 ounces. The weight of the plastic cylinder was .497 ounces per inch. The effect of these added masses on the frequencies was assumed negligible.

### Comparison of Frequency Measurement

The high speed movie camera method of frequency measurement proved very satisfactory, but also required a great deal of time. The camera had a neon bulb timing light built in which was energized by a 1000 cycle audio oscillator. The output of the oscillator was amplified through a CRO which provided a means of adjusting the light to the desired brightness. The only errors





that could be made in this method were (a) errors in counting the film and (b) frequency drift in the oscillator. Two separate runs were made on each length tested.

In order to speed up the experiment and reduce the amount of labor involved, it was decided to try frequency measurement with an electronic decade counter. If there is any frequency drift of the audio oscillator, the results of the decade counter will be more accurate than the movie camera since the decade counter records every second noting any change which may occur.

#### Boundary Effects in Water

To check for wall effects, the cylinder was submerged in the stability tank and the test rerun. The results obtained were the same as those observed in the towing tank test. A further check was made by varying the distance of the cylinder from the walls in the stability tank. Again no difference was noted. No attempt was made to vibrate the cylinder within four diameters of the wall.

#### Comparison with Different Cylinder

The necessity of re-checking the 30-inch cylinder arose after it had been cut down to 22 inches. A new 30-inch plastic tube was re-wound with approximately the same amount of wire as before. Both the air and water tests agreed identically with the previous 30-inch test.

#### Damping Effects of Rubber Band Stand-off

To ascertain whether the rubber band had any appreciable damping effect, the force necessary to stretch the rubber band one inch and the force required to deflect the tube one inch were calculated. To stretch the rubber band

(b) Government will be the beneficiary. For example, some have said we must

It is not to be expected that the Government will be able to do more than to make a few suggestions, and to leave the matter to the discretion of the local authorities. It is not to be expected that the Government will be able to do more than to make a few suggestions, and to leave the matter to the discretion of the local authorities.

It should be well known, the opinion you expressed in the evidence  
that the last year. The people of the world are now in a  
position in the world. A further check was made by testing the  
balance of the system from the world in the existing state. Again in  
the system was used. It always was used to provide the system with  
the balance of the world.

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1. The University of Wisconsin has been authorized to receive the Wisconsin National Guard and to provide for the training of the National Guard in the State of Wisconsin.

10. The results of the study show that the proposed method is effective in detecting and removing malicious code from the system. The results also show that the proposed method is able to detect and remove malicious code from the system in a timely manner. The results also show that the proposed method is able to detect and remove malicious code from the system in a timely manner.



one inch required a force of .61 pounds, and to deflect the cylinder one inch, a force of 454 pounds was necessary. The damping effect of the rubber band may be neglected.

#### Amplitude Measurement

The equipment used was not capable of measuring amplitudes. This is partly because the natural resonant period of the pick-up, 980 cycles per second, was within the range of the frequencies measured. The primary difficulty was that it was not possible to maintain a constant exciting force on the cylinder. There also was no means of accurately measuring the exciting force. A constant exciting force was not possible because a higher force was required to excite the higher modes, but this same force would cause the cylinder to be drawn hard against the faces of the electro-magnet poles at the lower modes. It was necessary therefore to start with relatively low driving forces at low modes and increase the force to excite the higher frequencies.

#### Computation of Virtual Mass

The virtual mass was computed assuming negligible damping so that

$$\frac{M_V}{M_T} = \left( \frac{f_1}{f_2} \right)^2 \quad (6)$$

where

$M_V$  = Virtual Mass

$M_T$  = Mass of Tube

$f_1$  = Frequency in Air

$f_2$  = Frequency in Water

1. The first step is to identify the problem or issue that needs to be addressed. This involves gathering information and understanding the context of the situation.

*Polymerized at 60°C for 20 min.*

Let

$M_W$  = Added Water Mass

$M_C$  = Displaced Water Mass

then

$$M_V = M_W + M_T \quad (7)$$

$$M_W = M_T \left[ \left( \frac{f_1}{f_2} \right)^2 - 1 \right] \quad (8)$$

and

$$\frac{M_W}{M_C} = \frac{M_T}{M_C} \left[ \left( \frac{f_1}{f_2} \right)^2 - 1 \right] \quad (9)$$

Thus the ratio  $\left( \frac{M_W}{M_C} \right)$  may be computed from the measured values of the frequencies.

#### Computation of K

Dr. H. M. Schauer<sup>(2)</sup> has derived an analytical expression for the mass ratio,  $\frac{M_W}{M_C}$ , as follows:

$$\frac{M_W}{M_C} = \frac{1}{1 + \eta \frac{iH_0(i\eta)}{-H_1(i\eta)}} \quad (10)$$

where  $H_0$  and  $H_1$  are Hankel functions and other symbols as previously defined.

The variation of the measured mass ratio from the above will be a function of  $\eta$  and the  $\frac{L}{D}$  ratio. This ratio can be expressed as a ratio, K

$$K = \frac{\text{measured mass ratio}}{\text{analytical mass ratio}} = \frac{(M_W/M_C)_M}{(M_W/M_C)_A} \quad (11)$$

and the other side of the  
 and the other side of the

(7)

(8)

$$M = M_0 + M_1 + M_2 + \dots$$

$$\left[ 1 - \left( \frac{M_1}{M_0} \right)^2 \right] M = M_0$$

and

(9)

$$\left[ 1 - \left( \frac{M_1}{M_0} \right)^2 \right] \frac{M}{M_0} = \frac{M}{M_0}$$

Thus the ratio  $\left( \frac{M}{M_0} \right)$  is the square root of the

expression.

### Derivation of A

Dr. J. W. Smith (10) has derived an equation for the ratio

$$\frac{M}{M_0} = \frac{1}{\sqrt{1 - \left( \frac{M_1}{M_0} \right)^2}}$$

(10)

$$\frac{M}{M_0} = \frac{1}{\sqrt{1 - \left( \frac{M_1}{M_0} \right)^2}}$$

where  $M_0$  and  $M_1$  are the total mass and the mass of the

The velocity of the moving mass is the same as the

time of  $t$  and the  $\frac{1}{t}$  ratio. This ratio can be written as a ratio  $\frac{1}{t}$

$$\frac{1}{t} = \frac{1}{\sqrt{1 - \left( \frac{M_1}{M_0} \right)^2}}$$

(11)

$$\frac{1}{t} = \frac{1}{\sqrt{1 - \left( \frac{M_1}{M_0} \right)^2}}$$



B. SUMMARY OF DATA AND CALCULATIONS

1. Definition of Symbols.

$f_1$  = Observed air frequency, cycles per second

$f_2$  = Observed water frequency, cycles per second

$M_w$  = Added mass of water

$M_o$  = Mass of displaced water

$L$  = Length of cylinder, inches

$D$  = Diameter of cylinder, inches

$\eta = \frac{D}{2L} (m + 1)$

$m$  = Mode number



# SECTION 101.101 TO 101.105

1. Section 101.101 to 101.105

2. Section 101.101 to 101.105

3. Section 101.101 to 101.105

4. Section 101.101 to 101.105

5. Section 101.101 to 101.105

6. Section 101.101 to 101.105

7. Section 101.101 to 101.105

8. Section 101.101 to 101.105

9. Section 101.101 to 101.105

10. Section 101.101 to 101.105

11. Section 101.101 to 101.105

12. Section 101.101 to 101.105

13.

14.

15. Section 101.101 to 101.105

16. Section 101.101 to 101.105

17. Section 101.101 to 101.105

18. Section 101.101 to 101.105

19.

20.

2. Calculated values of  $\frac{M_v}{M_c}$ .

MODE	$f_1$	$f_2$	$\frac{M_v}{M_c}$	$\eta$
1	61.7			
2	170.5	86.2	0.82	0.179
3	332.0	169.1	0.795	0.238
4	539.5	279.0	0.770	0.298
5	787.5	419.0	0.709	0.358

TABLE I

Test Results 52.7-inch Cylinder  $L/D = 26.35$

---

MODE	$f_1$	$f_2$	$\frac{M_v}{M_c}$	$\eta$
1	104.5	54	.792	.157
2	290.5	151	.768	.236
3	562	295	.742	.314
4	893	476	.711	.392
5	1277	692	.682	.471

TABLE II

Test Results of 40-inch cylinder  $L/D = 20$

$\theta$	$\frac{1}{\theta}$	$\frac{1}{\theta^2}$	$\frac{1}{\theta^3}$	RTN
100.0	0.0100	0.0001	0.00001	1
90.0	0.0111	0.000123	0.0000137	2
80.0	0.0125	0.000156	0.0000196	3
70.0	0.0143	0.000204	0.0000281	4
60.0	0.0167	0.000278	0.0000389	5

TABLE I

Test results of 10-sec. test - P. 12

$\theta$	$\frac{1}{\theta}$	$\frac{1}{\theta^2}$	$\frac{1}{\theta^3}$	RTN
100.0	0.0100	0.0001	0.00001	1
90.0	0.0111	0.000123	0.0000137	2
80.0	0.0125	0.000156	0.0000196	3
70.0	0.0143	0.000204	0.0000281	4
60.0	0.0167	0.000278	0.0000389	5

TABLE II

Test results of 10-sec. test - P. 12

MODE	$f_1$	$f_2$	$\frac{M}{M_0}$	$\eta$
1	114	59	0.773	0.166
2	313	163	0.761	0.249
3	602	319	0.727	0.332
4	943	509	0.685	0.415
5	1351	739.5	0.665	0.497

TABLE III

Test Results 38-inch Cylinder  $L/D = 19$

---

MODE	$f_1$	$f_2$	$\frac{M}{M_0}$	$\eta$
1	183	97.5	0.720	0.209
2	496.5	268.5	0.689	0.314
3	936	512	0.665	0.419
4	1454	808	0.637	0.523

Table IV

Test Results 30-inch Cylinder  $L/D = 15$

$f$	$\frac{C}{H}$	$C$	$H$	TIME
0.10	0.10	0.10	0.10	1
0.20	0.20	0.20	0.20	2
0.30	0.30	0.30	0.30	3
0.40	0.40	0.40	0.40	4
0.50	0.50	0.50	0.50	5

### TABLE II

Test results for 10-100-100-100-100-100

$f$	$\frac{C}{H}$	$C$	$H$	TIME
0.10	0.10	0.10	0.10	1
0.20	0.20	0.20	0.20	2
0.30	0.30	0.30	0.30	3
0.40	0.40	0.40	0.40	4

### TABLE III

Test results for 10-100-100-100-100-100



MODE	$f_1$	$f_2$	$\frac{M}{M_0}$	$\eta$
1	205	112	0.674	0.224
2	553	305	0.657	0.336
3	1036	581.5	0.622	0.448

TABLE V

Test Results 28-inch Cylinder  $L/D = 14$

---

MODE	$f_1$	$f_2$	$\frac{M}{M_0}$	$\eta$
1	299	172	0.590	0.286
2	800	465	0.570	0.428
3	1457	855	0.556	0.571

TABLE VI

Test Results 22-inch Cylinder  $L/D = 11$

$\mu$	$\frac{\mu}{\sigma}$	$\epsilon_1$	$\epsilon_2$	Order
100.0	100.0	100	100	1
99.0	99.0	100	99	2
98.0	98.0	100	98	3

TABLE I

Test results for  $\mu = 100$  and  $\sigma = 1$

$\mu$	$\frac{\mu}{\sigma}$	$\epsilon_1$	$\epsilon_2$	Order
100.0	100.0	100	100	1
99.0	99.0	100	99	2
98.0	98.0	100	98	3

TABLE II

Test results for  $\mu = 100$  and  $\sigma = 1$

$\eta$	$1H_o(1\eta)$	$-H_1(1\eta)$	$\frac{1H_o(1\eta)}{-H_1(1\eta)}$	$\eta \frac{1H_o(1\eta)}{-H_1(1\eta)}$	$1+\eta \frac{1H_o(1\eta)}{-H_1(1\eta)}$	$\frac{M_w}{M_o}$
.120	1.431	5.20	.275	.0330	1.0330	.968
.131	1.376	4.75	.290	.0380	1.0380	.963
.175	1.198	3.50	.342	.0599	1.0599	.943
.196	1.128	3.11	.363	.0711	1.0711	.934
.261	.9956	2.275	.438	.114	1.114	.898
.262	.9954	2.265	.439	.115	1.115	.897
.327	.8238	1.763	.437	.153	1.153	.867
.349	.7865	1.635	.481	.168	1.168	.856
.392	.7209	1.425	.506	.198	1.198	.835
.437	.6609	1.249	.529	.231	1.231	.812
.524	.5639	.9928	.568	.298	1.298	.770

TABLE VIII

Analytical Calculation of Virtual Mass

By Dr. H. M. Schauer<sup>(2)</sup>

$$\frac{M_w}{M_o} = \frac{1}{1 + \eta \frac{1H_o(1\eta)}{-H_1(1\eta)}}$$

$M_w$  = Added Water Mass

$M_o$  = Mass of Displaced Water

$M_T$  = Mass of Cylinder

$$\eta = (\pi+1) \frac{a}{L}$$

$\pi$  = Mode Number

$a$  = Radius

$L$  = Length

$\beta$	$\frac{\partial}{\partial \beta}$	$\frac{\partial}{\partial \beta}$	$\frac{\partial}{\partial \beta}$	NOTE
100.0	100.0	100	100	1
200.0	200.0	200	200	2
300.0	300.0	300	300	3

TABLE 1

Test results for the first set of data

Test results for the second set of data

$\beta$	$\frac{\partial}{\partial \beta}$	$\frac{\partial}{\partial \beta}$	$\frac{\partial}{\partial \beta}$	NOTE
100.0	100.0	100	100	1
200.0	200.0	200	200	2
300.0	300.0	300	300	3

TABLE 2

Test results for the first set of data

Test results for the second set of data

$\eta$	$1H_o(1\eta)$	$-H_1(1\eta)$	$\frac{1H_o(1\eta)}{-H_1(1\eta)}$	$\eta \frac{1H_o(1\eta)}{-H_1(1\eta)}$	$1+\eta \frac{1H_o(1\eta)}{-H_1(1\eta)}$	$\frac{M_w}{M_o}$
.120	1.431	5.20	.275	.0330	1.0330	.968
.131	1.376	4.75	.290	.0380	1.0380	.963
.175	1.198	3.50	.342	.0599	1.0599	.943
.196	1.128	3.11	.363	.0711	1.0711	.934
.261	.9956	2.275	.438	.114	1.114	.898
.262	.9954	2.265	.439	.115	1.115	.897
.327	.8238	1.763	.437	.153	1.153	.867
.349	.7865	1.635	.481	.168	1.168	.856
.392	.7209	1.425	.506	.198	1.198	.835
.437	.6609	1.249	.529	.231	1.231	.812
.524	.5639	.9928	.568	.298	1.298	.770

TABLE VIII

Analytical Calculation of Virtual Mass

By Dr. H. M. Schauer<sup>(2)</sup>

$$\frac{M_w}{M_o} = \frac{1}{1 + \eta \frac{1H_o(1\eta)}{-H_1(1\eta)}}$$

$M_w$  = Added Water Mass

$M_o$  = Mass of Displaced Water

$M_T$  = Mass of Cylinder

$$\eta = (\pi+1) \frac{a}{L}$$

$n$  = Mode Number

$a$  = Radius

$L$  = Length



$\frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$	$\frac{f_1(1)}{f_2(1)} \frac{H}{L}$
0.00	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.000	0.000	0.000	0.000	0.000	0.000
0.10	0.000	0.000	0.000	0.000	0.000	0.000
0.15	0.000	0.000	0.000	0.000	0.000	0.000
0.20	0.000	0.000	0.000	0.000	0.000	0.000
0.25	0.000	0.000	0.000	0.000	0.000	0.000
0.30	0.000	0.000	0.000	0.000	0.000	0.000
0.35	0.000	0.000	0.000	0.000	0.000	0.000
0.40	0.000	0.000	0.000	0.000	0.000	0.000
0.45	0.000	0.000	0.000	0.000	0.000	0.000
0.50	0.000	0.000	0.000	0.000	0.000	0.000
0.55	0.000	0.000	0.000	0.000	0.000	0.000
0.60	0.000	0.000	0.000	0.000	0.000	0.000
0.65	0.000	0.000	0.000	0.000	0.000	0.000
0.70	0.000	0.000	0.000	0.000	0.000	0.000
0.75	0.000	0.000	0.000	0.000	0.000	0.000
0.80	0.000	0.000	0.000	0.000	0.000	0.000
0.85	0.000	0.000	0.000	0.000	0.000	0.000
0.90	0.000	0.000	0.000	0.000	0.000	0.000
0.95	0.000	0.000	0.000	0.000	0.000	0.000
1.00	0.000	0.000	0.000	0.000	0.000	0.000

# APPENDIX

ANALYTICAL EXPRESSIONS OF VARIOUS CASES

(a) For the case of a cylinder

$$\frac{1}{f_1(1)} \frac{f_2(1)}{f_1(1)} \frac{H}{L} = \frac{H}{L}$$

$H_0$  = Head Water Level

$H_0$  = Head of the cylinder

$H_0$  = Head of the cylinder

$$\frac{H}{L} = (m+1) \frac{H}{L}$$

$H$  = Head Water Level

$L$  = Length

$L$  = Length

3. Calculated values of K.

$\eta$	$(M_w/M_o)_M$	$(M_w/M_o)_A$	K
.2	.811	.933	.870
.25	.792	.910	.870
.30	.772	.886	.870
.35	.750	.860	.870
.40	.730	.833	.876

TABLE IX (a)

Values of K  $L/D = 26.35$

---

$\eta$	$(M_w/M_o)_M$	$(M_w/M_o)_A$	K
.2	.772	.933	.829
.25	.754	.910	.829
.30	.737	.886	.830
.35	.718	.810	.834
.40	.700	.833	.840
.45	.683	.805	.847
.50	.665	.776	.856

TABLE IX (b)

Values of K  $L/D = 19$



$\eta$	$(M_w/M_c)_M$	$(M_w/M_c)_A$	K
.2	.72	.933	.772
.25	.707	.910	.776
.30	.694	.886	.784
.35	.682	.860	.793
.40	.668	.833	.802
.45	.656	.805	.816
.50	.643	.776	.829

TABLE IX (c)

Values of K  $L/D = 15$

---

$\eta$	$(M_w/M_c)_M$	$(M_w/M_c)_A$	K
.2	.677	.933	.726
.25	.667	.910	.734
.30	.657	.886	.741
.35	.648	.860	.754
.40	.639	.833	.767
.45	.629	.805	.781
.50	.619	.776	.796

TABLE IX (d)

Values of K  $L/D = 14$

$\lambda$	$\lambda \left( \frac{1}{\sqrt{2}} \right)$	$\lambda \left( \frac{1}{\sqrt{2}} \right)$	$\lambda$
0.0	0.0	0.0	0.0
0.1	0.1	0.1	0.1
0.2	0.2	0.2	0.2
0.3	0.3	0.3	0.3
0.4	0.4	0.4	0.4
0.5	0.5	0.5	0.5
0.6	0.6	0.6	0.6
0.7	0.7	0.7	0.7
0.8	0.8	0.8	0.8
0.9	0.9	0.9	0.9
1.0	1.0	1.0	1.0

TABLE II

Values of  $\lambda$  for  $\lambda = 1.0$

$\lambda$	$\lambda \left( \frac{1}{\sqrt{2}} \right)$	$\lambda \left( \frac{1}{\sqrt{2}} \right)$	$\lambda$
0.0	0.0	0.0	0.0
0.1	0.1	0.1	0.1
0.2	0.2	0.2	0.2
0.3	0.3	0.3	0.3
0.4	0.4	0.4	0.4
0.5	0.5	0.5	0.5
0.6	0.6	0.6	0.6
0.7	0.7	0.7	0.7
0.8	0.8	0.8	0.8
0.9	0.9	0.9	0.9
1.0	1.0	1.0	1.0

TABLE III

Values of  $\lambda$  for  $\lambda = 1.0$



$\eta$	$(M_w/M_o)_M$	$(M_w/M_o)_A$	K
.2	.600	.933	.644
.25	.595	.910	.654
.30	.590	.886	.664
.35	.585	.860	.676
.40	.577	.833	.690
.45	.571	.805	.706
.50	.565	.776	.726

TABLE IX (e)

Values of K  $L/D = 11$

---

$\eta$	$(M_w/M_o)_M$	$(M_w/M_o)_A$	K
.15	.800	.954	.839
.224	.782	.922	.849
.30	.753	.886	.849
.40	.712	.833	.855
.50	.674	.776	.869

TABLE IX (f)

Values of K  $L/D = 21$

$i$	$\lambda_i(\sqrt{N})$	$\mu_i(\sqrt{N})$	$\rho_i$
100.	0.00.	0.00.	0.
105.	0.05.	0.05.	0.01.
110.	0.10.	0.10.	0.02.
115.	0.15.	0.15.	0.03.
120.	0.20.	0.20.	0.04.
125.	0.25.	0.25.	0.05.
130.	0.30.	0.30.	0.06.

TABLE II

$N = 100$   $\lambda_i(\sqrt{N})$   $\mu_i(\sqrt{N})$

$i$	$\lambda_i(\sqrt{N})$	$\mu_i(\sqrt{N})$	$\rho_i$
100.	0.00.	0.00.	0.
105.	0.05.	0.05.	0.01.
110.	0.10.	0.10.	0.02.
115.	0.15.	0.15.	0.03.
120.	0.20.	0.20.	0.04.
125.	0.25.	0.25.	0.05.

TABLE III

$N = 100$   $\lambda_i(\sqrt{N})$   $\mu_i(\sqrt{N})$

### C. SAMPLE CALCULATIONS

#### 1. Theoretical frequency of free-free bar vibrating in air.

$$f = \frac{m_n^2}{2\pi} \left[ \frac{EK^2g}{\gamma} \right]^{1/2}$$

where  $m_n$  = 4.730 for first mode

E = Modulus of elasticity

= 580,000 psi for Lucite (approx.)

$\gamma$  = Specific gravity = 1.18

g = 386 in/sec<sup>2</sup>

k = Radius of gyration of section

$k^2$  = .441

$$f = \frac{.0081}{6.28} \frac{580,000 \times .441}{11.05 \times 10^{-5}}^{1/2}$$

= 62.0 cycles per second

for 2 noded frequency of 52.7-inch cylinder.

#### 2. Calculation of $\frac{M_w}{M_c}$ .

$$\frac{M_w}{M_c} = \frac{M_T}{M_c} \left[ \left( \frac{f_1}{f_2} \right)^2 - 1 \right]$$

where  $M_w$  = Added water mass

$M_c$  = Displaced water mass

$M_T$  = Mass of tube

# 2. THEORETICAL FRAMEWORK

1. Theoretical Framework of the Proposed Method

$$r = \frac{1}{\sqrt{2}} \left[ \frac{1}{\sqrt{2}} \right]$$

- where  $r = 1/\sqrt{2}$  for first order
- $k = 1$  for second order
- $k = 2$  for third order
- $k = 3$  for fourth order
- $k = 4$  for fifth order
- $k = 5$  for sixth order
- $k = 6$  for seventh order
- $k = 7$  for eighth order
- $k = 8$  for ninth order
- $k = 9$  for tenth order
- $k = 10$  for eleventh order
- $k = 11$  for twelfth order
- $k = 12$  for thirteenth order
- $k = 13$  for fourteenth order
- $k = 14$  for fifteenth order
- $k = 15$  for sixteenth order
- $k = 16$  for seventeenth order
- $k = 17$  for eighteenth order
- $k = 18$  for nineteenth order
- $k = 19$  for twentieth order
- $k = 20$  for twenty-first order
- $k = 21$  for twenty-second order
- $k = 22$  for twenty-third order
- $k = 23$  for twenty-fourth order
- $k = 24$  for twenty-fifth order
- $k = 25$  for twenty-sixth order
- $k = 26$  for twenty-seventh order
- $k = 27$  for twenty-eighth order
- $k = 28$  for twenty-ninth order
- $k = 29$  for thirtieth order
- $k = 30$  for thirty-first order
- $k = 31$  for thirty-second order
- $k = 32$  for thirty-third order
- $k = 33$  for thirty-fourth order
- $k = 34$  for thirty-fifth order
- $k = 35$  for thirty-sixth order
- $k = 36$  for thirty-seventh order
- $k = 37$  for thirty-eighth order
- $k = 38$  for thirty-ninth order
- $k = 39$  for fortieth order
- $k = 40$  for forty-first order
- $k = 41$  for forty-second order
- $k = 42$  for forty-third order
- $k = 43$  for forty-fourth order
- $k = 44$  for forty-fifth order
- $k = 45$  for forty-sixth order
- $k = 46$  for forty-seventh order
- $k = 47$  for forty-eighth order
- $k = 48$  for forty-ninth order
- $k = 49$  for fiftieth order
- $k = 50$  for fifty-first order
- $k = 51$  for fifty-second order
- $k = 52$  for fifty-third order
- $k = 53$  for fifty-fourth order
- $k = 54$  for fifty-fifth order
- $k = 55$  for fifty-sixth order
- $k = 56$  for fifty-seventh order
- $k = 57$  for fifty-eighth order
- $k = 58$  for fifty-ninth order
- $k = 59$  for sixtieth order
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- $k = 63$  for sixty-fourth order
- $k = 64$  for sixty-fifth order
- $k = 65$  for sixty-sixth order
- $k = 66$  for sixty-seventh order
- $k = 67$  for sixty-eighth order
- $k = 68$  for sixty-ninth order
- $k = 69$  for seventieth order
- $k = 70$  for seventy-first order
- $k = 71$  for seventy-second order
- $k = 72$  for seventy-third order
- $k = 73$  for seventy-fourth order
- $k = 74$  for seventy-fifth order
- $k = 75$  for seventy-sixth order
- $k = 76$  for seventy-seventh order
- $k = 77$  for seventy-eighth order
- $k = 78$  for seventy-ninth order
- $k = 79$  for eightieth order
- $k = 80$  for eighty-first order
- $k = 81$  for eighty-second order
- $k = 82$  for eighty-third order
- $k = 83$  for eighty-fourth order
- $k = 84$  for eighty-fifth order
- $k = 85$  for eighty-sixth order
- $k = 86$  for eighty-seventh order
- $k = 87$  for eighty-eighth order
- $k = 88$  for eighty-ninth order
- $k = 89$  for ninetieth order
- $k = 90$  for ninety-first order
- $k = 91$  for ninety-second order
- $k = 92$  for ninety-third order
- $k = 93$  for ninety-fourth order
- $k = 94$  for ninety-fifth order
- $k = 95$  for ninety-sixth order
- $k = 96$  for ninety-seventh order
- $k = 97$  for ninety-eighth order
- $k = 98$  for ninety-ninth order
- $k = 99$  for one hundredth order

$$r = \frac{1}{\sqrt{2}} \left[ \frac{1}{\sqrt{2}} \right]$$

For a higher order of the proposed method

2. Calculation of  $\frac{1}{\sqrt{2}}$

$$\left[ \frac{1}{\sqrt{2}} \right] = \frac{1}{\sqrt{2}}$$

- where  $r = 1/\sqrt{2}$  for first order
- $k = 1$  for second order
- $k = 2$  for third order
- $k = 3$  for fourth order
- $k = 4$  for fifth order
- $k = 5$  for sixth order
- $k = 6$  for seventh order
- $k = 7$  for eighth order
- $k = 8$  for ninth order
- $k = 9$  for tenth order
- $k = 10$  for eleventh order
- $k = 11$  for twelfth order
- $k = 12$  for thirteenth order
- $k = 13$  for fourteenth order
- $k = 14$  for fifteenth order
- $k = 15$  for sixteenth order
- $k = 16$  for seventeenth order
- $k = 17$  for eighteenth order
- $k = 18$  for nineteenth order
- $k = 19$  for twentieth order
- $k = 20$  for twenty-first order
- $k = 21$  for twenty-second order
- $k = 22$  for twenty-third order
- $k = 23$  for twenty-fourth order
- $k = 24$  for twenty-fifth order
- $k = 25$  for twenty-sixth order
- $k = 26$  for twenty-seventh order
- $k = 27$  for twenty-eighth order
- $k = 28$  for twenty-ninth order
- $k = 29$  for thirtieth order
- $k = 30$  for thirty-first order
- $k = 31$  for thirty-second order
- $k = 32$  for thirty-third order
- $k = 33$  for thirty-fourth order
- $k = 34$  for thirty-fifth order
- $k = 35$  for thirty-sixth order
- $k = 36$  for thirty-seventh order
- $k = 37$  for thirty-eighth order
- $k = 38$  for thirty-ninth order
- $k = 39$  for fortieth order
- $k = 40$  for forty-first order
- $k = 41$  for forty-second order
- $k = 42$  for forty-third order
- $k = 43$  for forty-fourth order
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- $k = 45$  for forty-sixth order
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- $k = 48$  for forty-ninth order
- $k = 49$  for fiftieth order
- $k = 50$  for fifty-first order
- $k = 51$  for fifty-second order
- $k = 52$  for fifty-third order
- $k = 53$  for fifty-fourth order
- $k = 54$  for fifty-fifth order
- $k = 55$  for fifty-sixth order
- $k = 56$  for fifty-seventh order
- $k = 57$  for fifty-eighth order
- $k = 58$  for fifty-ninth order
- $k = 59$  for sixtieth order
- $k = 60$  for sixty-first order
- $k = 61$  for sixty-second order
- $k = 62$  for sixty-third order
- $k = 63$  for sixty-fourth order
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- $k = 66$  for sixty-seventh order
- $k = 67$  for sixty-eighth order
- $k = 68$  for sixty-ninth order
- $k = 69$  for seventieth order
- $k = 70$  for seventy-first order
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- $k = 72$  for seventy-third order
- $k = 73$  for seventy-fourth order
- $k = 74$  for seventy-fifth order
- $k = 75$  for seventy-sixth order
- $k = 76$  for seventy-seventh order
- $k = 77$  for seventy-eighth order
- $k = 78$  for seventy-ninth order
- $k = 79$  for eightieth order
- $k = 80$  for eighty-first order
- $k = 81$  for eighty-second order
- $k = 82$  for eighty-third order
- $k = 83$  for eighty-fourth order
- $k = 84$  for eighty-fifth order
- $k = 85$  for eighty-sixth order
- $k = 86$  for eighty-seventh order
- $k = 87$  for eighty-eighth order
- $k = 88$  for eighty-ninth order
- $k = 89$  for ninetieth order
- $k = 90$  for ninety-first order
- $k = 91$  for ninety-second order
- $k = 92$  for ninety-third order
- $k = 93$  for ninety-fourth order
- $k = 94$  for ninety-fifth order
- $k = 95$  for ninety-sixth order
- $k = 96$  for ninety-seventh order
- $k = 97$  for ninety-eighth order
- $k = 98$  for ninety-ninth order
- $k = 99$  for one hundredth order

For second mode of 52.7-inch bar

$$W_T = W_t/\text{in.} \times L + W_t.\text{clamp} + W_t.\text{Pickup} + W_t.\text{Exciting wire}$$

$$M_T = \frac{.497 \times 52.7 + .373 + .303}{16 \times 32.2}$$

$$= 0.0521$$

$$M_e = \frac{\pi D^2 L \gamma_w}{4g}$$

$$= \frac{3.14 \times 4 \times 52.7 \times 62.4}{4 \times 32.2 \times 1728}$$

$$= 0.186$$

$$f_1 = 170.5$$

$$f_2 = 86.2$$

$$\frac{M_T}{M_e} = .280(2.92)$$

$$= 0.820$$

### 3. Calculation of K.

By definition

$$K = \frac{M_w/M_e \text{ measured}}{M_w/M_e \text{ analytically computed}}$$

For 52.7" cylinder

when  $\eta = .2$

$$\left(\frac{M_w}{M_e}\right)_M = .811$$

$$\left(\frac{M_w}{M_e}\right)_A = .933$$

Hence  $K = \frac{.811}{.933} = 0.870$



For second mode of vibration

$$M_2 = M_1 \left( 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots \right) = M_1 \left( 1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots \right)$$

$$M_2 = \frac{M_1 (1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots)}{1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots}$$

$$M_2 = 0.196 M_1$$

$$M_2 = \frac{M_1 \left( \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots \right)}{1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots}$$

$$M_2 = \frac{M_1 \left( \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots \right)}{1 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots}$$

$$M_2 = 0.196 M_1$$

$$M_2 = 0.196 M_1$$

$$M_2 = 0.196 M_1$$

$$M_2 = 0.196 M_1$$

$$(M_2)_{max} = 0.196 M_1$$

$$M_2 = 0.196 M_1$$

3. Calculation of  $K$

By definition

$$K = \frac{M_2}{M_1} = \frac{0.196 M_1}{M_1} = 0.196$$

For 2nd mode

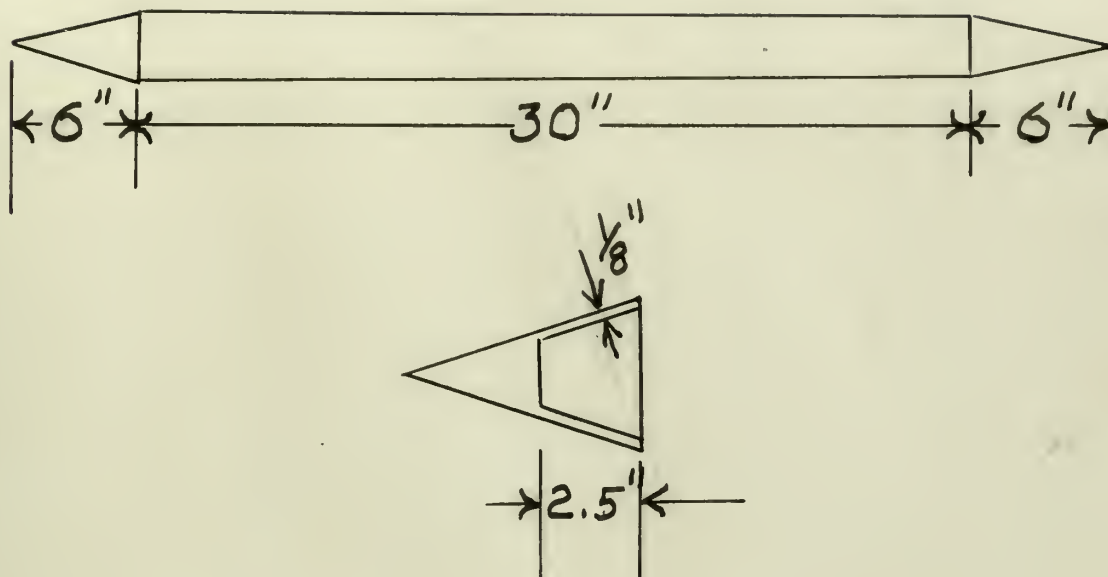
$$K = \frac{M_2}{M_1} = \frac{0.196 M_1}{M_1} = 0.196$$

$$K = \frac{M_2}{M_1} = \frac{0.196 M_1}{M_1} = 0.196$$

$$K = \frac{M_2}{M_1} = \frac{0.196 M_1}{M_1} = 0.196$$

$$K = \frac{M_2}{M_1} = \frac{0.196 M_1}{M_1} = 0.196$$

4.



The center of gravity of cones is approximately 3" from the base. Let us assume this body to be equivalent to a right circular cylinder 36 inches in length.

This assumption may be checked by calculating the air frequency of a 36-inch cylinder.

$$f = \frac{n^2}{2\pi} \left( \frac{EK^2g}{\gamma} \right)^{1/2}$$

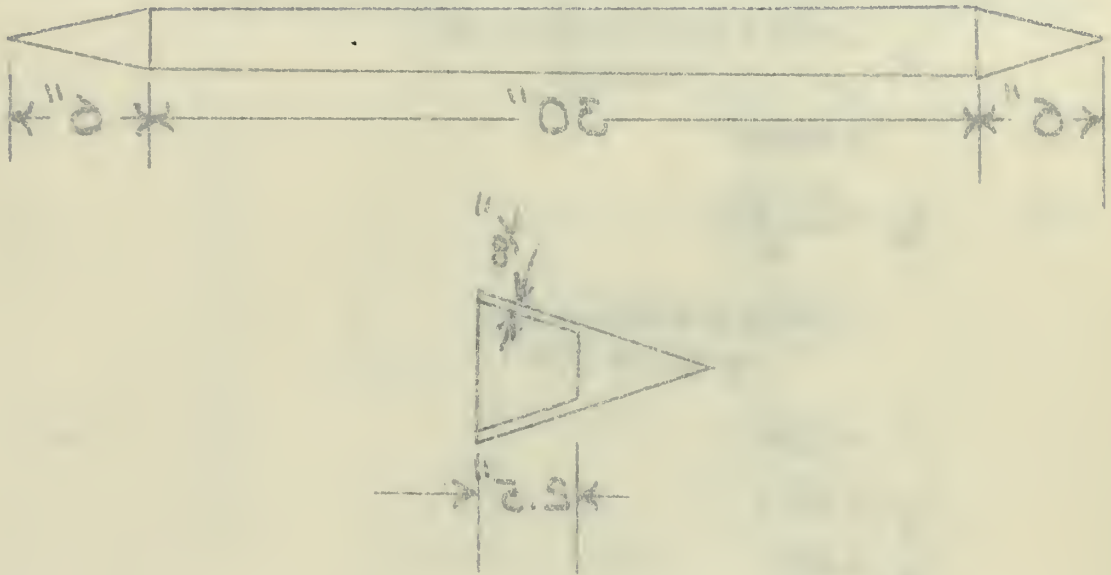
where  $\frac{1}{2\pi} \left( \frac{EK^2g}{\gamma} \right)^{1/2} = 7,350$

$n = \frac{4,730}{L}$  for 2 noded frequency

$f = \left( \frac{4,730}{36} \right)^2 7350$

$f = 127 \text{ cps}$

Observed frequency was 131 cps, therefore equivalent length is 35.5 inches.



The center of gravity of a tapered shaft is located at a distance of 10 inches from the larger end. The center of gravity of a tapered shaft is located at a distance of 10 inches from the larger end. The center of gravity of a tapered shaft is located at a distance of 10 inches from the larger end.

$$\begin{aligned}
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3 \\
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3 \\
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3 \\
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3 \\
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3 \\
 & \frac{1}{2} \pi r^2 h = \frac{1}{2} \pi (0.5)^2 (30) = 11.78 \text{ in}^3
 \end{aligned}$$

The center of gravity of a tapered shaft is located at a distance of 10 inches from the larger end.

The water frequency now may be computed using Prof. Lewis' J, corrected by K for a 42-inch right circular cylinder

$$f = \left( \frac{4.730}{35.5} \right)^2 (7350) \left( \frac{M_T}{M_T + M_W} \right)^{1/2}$$

where  $M_T = .036$

$$M_W = JKM_G \quad (12)$$

$$= (.947) (.839) (.120)$$

$$M_W = .0952$$

$$M_W + M_T = .1312$$

$$f = 68.9 \text{ cps.}$$

The experimental results gave a water frequency of 70 cps.

For the second mode

$$J = .923$$

$$K = .849$$

$$M_W = .0940$$

$$M_W + M_T = .1300$$

$$f = 187 \text{ cps}$$

Experimental results gave a water frequency of 188 cps.

The above expression may be simplified using the following relation:  
for a linear elastic material:

$$\frac{1}{2} \left( \frac{d}{d\epsilon} \right) \left( \frac{d\sigma}{d\epsilon} \right) = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right) = \sigma$$

(2)

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right) \left( \frac{d\epsilon}{d\sigma} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

The experimental results give a value of  $\sigma = 100$  MPa.

For the second case:

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

$$\sigma = \frac{1}{2} \left( \frac{d\sigma}{d\epsilon} \right)$$

Experimental results give a value of  $\sigma = 100$  MPa.



D. ORIGINAL DATA

1. The following data was taken using the decade counter.

<u>MODE</u>	<u>FREQUENCIES</u>			<u>AVERAGE</u>
1	114	114	114	114
2	313	313	313	313
3	604	601	602	602
4	944	942	942	943
5	1352	1350	1351	1351

TABLE X

Air Frequencies 38-inch Cylinder

---

<u>MODE</u>	<u>FREQUENCIES</u>			<u>AVERAGE</u>
1	59	59	59	59
2	163	163	163	163
3	320	319	319	319
4	510	507	509	509
5	740	739	739.5	739.5

TABLE XI

Water Frequencies 38-inch Cylinder

# TABLE I

1. The following data were taken at the various points.

DATE	TIME	TEMPERATURE	WIND	WAVE
1	11.4	11.1	11.4	11.4
2	11.3	11.3	11.3	11.3
3	11.2	11.2	11.2	11.2
4	11.1	11.1	11.1	11.1
5	11.0	11.0	11.0	11.0

# TABLE II

2. The following data were taken at the various points.

DATE	TIME	TEMPERATURE	WIND	WAVE
1	11.4	11.1	11.4	11.4
2	11.3	11.3	11.3	11.3
3	11.2	11.2	11.2	11.2
4	11.1	11.1	11.1	11.1
5	11.0	11.0	11.0	11.0

# TABLE III

3. The following data were taken at the various points.

MODE	FREQUENCIES				AVERAGE
1	182	183	183	183	183
2	496.5	495.5	496.5	496.5	496.5
3	933	936	935.5	936.5	936.0
4	1454.5	1453.5	1453	1454.5	1454.0

TABLE XII

Air Frequencies 30-inch Cylinder

---

MODE	FREQUENCIES				AVERAGE
1	98	97.5	97.5	97.5	97.5
2	268.5	269	267	268.5	268.5
3	510	513	513.5	511	512.0
4	810	809	808	807.5	808

TABLE XIII

Water Frequencies 30-inch Cylinder

DATE	DESCRIPTION	AMOUNT	DATE	DESCRIPTION	AMOUNT
1945	1945	1945	1945	1945	1945
1946	1946	1946	1946	1946	1946
1947	1947	1947	1947	1947	1947
1948	1948	1948	1948	1948	1948

### TABLE III

Table showing the results of the experiment.

DATE	DESCRIPTION	AMOUNT	DATE	DESCRIPTION	AMOUNT
1945	1945	1945	1945	1945	1945
1946	1946	1946	1946	1946	1946
1947	1947	1947	1947	1947	1947
1948	1948	1948	1948	1948	1948

### TABLE IV

Table showing the results of the experiment.

MODE	FREQUENCIES		AVERAGE
1	205	205	205
2	553	552.5	553
3	1036	1035.5	1036

TABLE XIV

Air Frequencies 28-inch Cylinder

-----

MODE	FREQUENCIES		AVERAGE
1	112	112	112
2	305	305	305
3	581.5	581.5	581.5
4	916	917	916.5

TABLE XV

Water Frequencies 28-inch Cylinder



	DATA	REMARKS	DATE
1	200	200	200
2	100	100	100
3	100	100	100

# VII. DATA

After inspection of the data

	DATA	REMARKS	DATE
1	100	100	100
2	200	200	200
3	100	100	100
4	100	100	100

# VIII. DATA

After inspection of the data

MODE	FREQUENCIES			AVERAGE
1	298	299.5	298.5	299
2	800	801	800	800
3	1457	1458	1457	1457

TABLE XVI

Air Frequencies 22-inch Cylinder

-----

MODE	FREQUENCIES			AVERAGE
1	171	171	172	171
2	465	466	465	465
3	854	855	855	855

TABLE XVII

Water Frequencies 22-inch Cylinder

DATE	DESCRIPTION	AMOUNT	DATE	DESCRIPTION
1912	1912	1912	1912	1912
1913	1913	1913	1913	1913
1914	1914	1914	1914	1914

# TABLE I

Notes: (1) The figures are in millions of dollars.

DATE	DESCRIPTION	AMOUNT	DATE	DESCRIPTION
1912	1912	1912	1912	1912
1913	1913	1913	1913	1913
1914	1914	1914	1914	1914

# TABLE II

Notes: (1) The figures are in millions of dollars.

MODE	FREQUENCIES				AVERAGE
1	104	105	105	104	104.5
2	291	290	291	290	290.5
3	561.5	562	562	562	562
4	891	894	893	893	893
5	1278	1276	1276	1277	1277

TABLE XVIII

Air Frequencies 40-inch Cylinder

---

MODE	FREQUENCIES				AVERAGE
1	54.0	54.0	53.5	54.0	54.0
2	150.0	151.0	151	151	151
3	296	294	295	295	295
4	477	476.5	476	476	476
5	693	691	692	691.5	692

TABLE XIX

Water Frequencies 40-inch Cylinder

ITEM	PERCENTAGE				ADJUSTED
1	104	104	104	104	104.0
2	104	104	104	104	104.0
3	104.2	104	104	104	104.2
4	104	104	104	104	104.0
5	104	104	104	104	104.0

TABLE III

The Programmed Air-Sea Operations

ITEM	PERCENTAGE				ADJUSTED
1	104.0	104.0	104.0	104.0	104.0
2	104.0	104.0	104.0	104.0	104.0
3	104	104	104	104	104.0
4	104.2	104	104	104	104.2
5	104	104	104	104.2	104.2

TABLE IV

Water Transported to the Gulf



MODE	FREQUENCIES			AVERAGE
1	131	131	131	131
2	353	351	352	352
3	659	658	658	658
4	1016	1020	1014	1017
5	1417	1419	1415	1417

TABLE XX

Air Frequencies 30-inch Cylinder  
with 6-inch Conical Ends

---

MODE	FREQUENCIES			AVERAGE
1	70	70	70	70
2	188	188	188	188
3	358	355	352	355
4	555	555	555	555
5	796	790	790	792

TABLE XXI

Water Frequencies 30-inch Cylinder  
with 6-inch Conical Ends

DATE	DESCRIPTION	AMOUNT
1911	1911	100
1912	1912	100
1913	1913	100
1914	1914	100
1915	1915	100

# TABLE II

Water Pumping Station Cylinder  
with Piston and Rod

DATE	DESCRIPTION	AMOUNT
1911	1911	100
1912	1912	100
1913	1913	100
1914	1914	100
1915	1915	100

# TABLE III

Water Pumping Station Cylinder  
with Piston and Rod

2. The following data was taken using the high speed movie camera.

MODE	FREQUENCIES		AVERAGE
1	61.7	61.7	61.7
2	170.5	170.5	170.5
3	332.0	332.0	332.0
4	539.5	539.5	539.5
5	787.5	787.5	787.5

TABLE XXII

Air Frequencies 52.7-inch Cylinder

-----

MODE	FREQUENCIES		AVERAGE
1			
2	86.2	86.2	86.2
3	169.1	169.1	169.1
4	279.0	279.0	279.0
5	419.0	419.0	419.0

TABLE XXIII

Water Frequencies 52.7-inch Cylinder

3. The following table shows the results of the tests made on the

TEMPERATURE	RELATIVE HUMIDITY	PERCENTAGE	WATER
100.0	100.0	100.0	1
100.1	100.1	100.1	2
100.2	100.2	100.2	3
100.3	100.3	100.3	4
100.4	100.4	100.4	5

### TABLE II

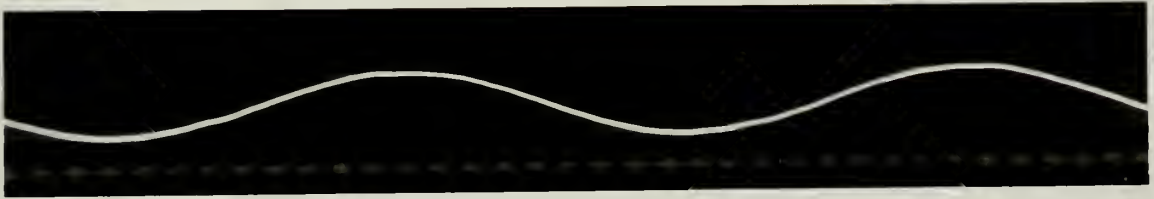
Results of tests made on the

TEMPERATURE	RELATIVE HUMIDITY	PERCENTAGE	WATER
100.0	100.0	100.0	1
100.1	100.1	100.1	2
100.2	100.2	100.2	3
100.3	100.3	100.3	4
100.4	100.4	100.4	5

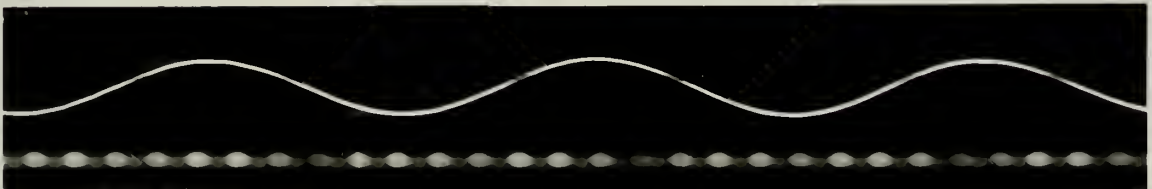
### TABLE III

Results of tests made on the

FIGURE VI  
PHOTOGRAPHS OF TYPICAL TWO NODED FREQUENCIES



TWO NODED WATER FREQUENCY



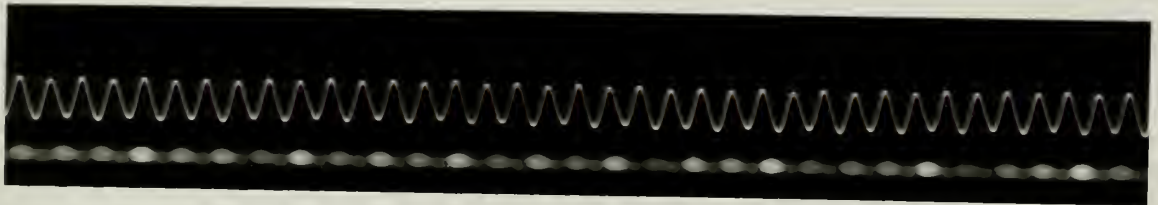
TWO NODED AIR FREQUENCY



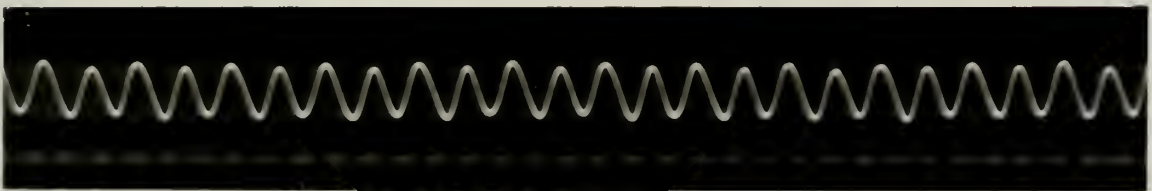


FIGURE VII

PHOTOGRAPHS OF TYPICAL SIX NODED FREQUENCIES



SIX NODED AIR FREQUENCY



SIX NODED WATER FREQUENCY



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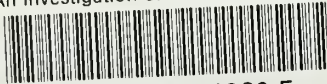
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